A Sequence-Scheduled and Query-Based MAC Protocol for Underwater Acoustic Networks with a Mobile Node

Jing Huang, Cheng Chi, Wei Wang, Haining Huang

***Abstract*—Since mobile nodes such as autonomous underwater vehicles can effectively expand network coverage, underwater acoustic networks with mobile nodes have attracted more and more attention in recent years. To ensure the timely access of a mobile node without disturbing the normal transmission of data packets from static nodes, a sequence-scheduled and query-based medium access control protocol is proposed in this paper. The underwater nodes with data packets to be transmitted reply with a control packet for channel reservation after receiving the broadcast control packet of the buoy, then the reserved nodes transmit their data packets as the order calculated by the buoy. We develop a mechanism to adjust the transmission order of the control packets sent by the underwater nodes in the handshake phase to reduce the collision and guarantee the success rate of reservation, and a query is initiated when the reserved control packet of the mobile node is not received by the buoy in the handshake to respond to the data transmission request of the mobile node in time. Simulations show that the maximum nodal throughput of the proposed MAC protocol increases by at least 20% and the access delay of the mobile node decreases by about 90%, compared to the two reference protocols. Besides, the average access probability of the mobile node in the proposed protocol is more than 90%.**

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I. INTRODUCTION

Mobile nodes such as autonomous underwater vehicles (AUVs) and underwater gliders have been widely applied in monitoring underwater environment[1] in recent years. With the capability of continuous monitoring, underwater acoustic networks (UANs) including mobile and static nodes are becoming increasingly attractive[2,3].

The objective of a medium access control (MAC) protocol is to schedule the shared channel for multiple nodes fairly and to reduce the collision of data packets transmitted by different nodes[4] as much as possible. Since the peculiar features of underwater acoustic channels such as low propagation speed (about 1 500 m/s[5], which is 2×10^5 times slower than the speed of radio), limited bandwidth (the range-rate product of current acoustic communication system is up to 40 km·bit/s[6]) and time variant multi-path[7], the existing MAC protocol for radio networks cannot be applied directly to UANs[8]. Designing a good medium access control (MAC) protocol is crucial for UANs. For the UANs including both static and mobile nodes, the design of an MAC protocol requires to consider two problems. The first is how to overcome the spatial-temporal uncertainty[9] caused by the long propagation delay and reduce collision probability of data packets. The second is how to ensure a high throughput of static nodes, while responding to the data packets transmission requirements of the mobile node in time.

To solve the fore-mentioned two problems, we propose the sequence-scheduled and query-based MAC (SQ-MAC) protocol. This protocol is receiver-initiated[10], which can avoid the sender-receiver collision[11] effectively caused by the long propagation delay. Based on this, a mechanism to adjust the transmission order of the reserved control packets sent by different underwater nodes is developed to ensure the success rate of reservation and the ant colony algorithm[12] is adopted as Ref. [13] to schedule the transmission order of data packets to improve the channel utilization. In addition, an active query is subjoined when the reserved control packet of the mobile node is not received by the buoy after the handshake to timely respond to the data packets transmission request of the mobile node.

The remainder of this paper is organized as follows. In section II, we describe briefly some related work in designing MAC protocols with mobility support for underwater acoustic networks. In section III, the SQ-MAC protocol is proposed for fully connected underwater acoustic networks with a mobile node. Simulations are carried out to evaluate the performance of the proposed protocol in section IV. Finally, the conclusions are provided in section V.

II. Related Work

Several MAC protocols have been proposed for UANs. They can be divided into two types: schedule-based and contention-based. The schedule-based protocols mainly include time division multiple access (TDMA)[14,15], code division multiple access (CDMA)[16], frequency division multiple access (FDMA)[17] and their variants. The contention-based protocols include random access named ALOHA[18,19], carrier sense multiple access (CSMA)[20] and handshake-based multiple access with collision avoidance (MACA)[21].

Regarding the MAC protocol design of UANs with mobile nodes, relevant research has also been studied. In Ref. [22], a protocol named communication-constrained data collection problem (CC-DCP) is proposed for collecting data from an underwater static network using an AUV. The protocol includes three stages, namely, initiation, scheduling and data transmission. Based on the assumption that all nodes in the network have completed time synchronization, the mobile node initiates the wake-up to static nodes and starts the data transmission. This protocol does not consider the case where the mobile node and static nodes interact with the same receiver. Conflict-free (CF) MAC[23] is similar to CC-DCP, only after the mobile node receives data packets from the static nodes, it replies to different types of ACK control packets to awake the next transmission while completing the confirmation, or notifies static nodes to retransmit the data. This protocol is also only applicable to the case where the mobile node collects data from static nodes, without considering the data interaction among static nodes. Ref. [24] considers the normal data interaction between underwater static nodes and the buoy and proposes the location-based TDMA (LTM) MAC. This protocol allocates the time slot length to each static node according to the traffic load. Before transmitting data packets, the static node needs to perform carrier sensing to obtain the access information of the mobile node. When the mobile node has a data transmission request, the transmission of the static node is postponed until the transmission of the mobile node is completed. But this protocol requires the mobile node to be within the communication range of all static nodes in the network so that static nodes can receive the access command of the mobile node.

In Ref. [25], NOH et al. proposed the delay aware opportunistic transmission scheduling (DOTS) MAC, leveraging the long propagation delay of underwater acoustic channel. The mobile node schedules its own transmission by passively listening to the transmission of the neighboring node and it can opportunistically realize parallel transmission to improve the channel utilization rate when the collision-free access conditions are satisfied. However, the performance is degraded under a high traffic load and dense node distribution. A handshake based ordered scheduling MAC (HOSM) is proposed in Ref. [13]. It applies the improved maximum and minimum ant colony algorithm to plan the data transmission order of each reserved node, which not only improves the network throughput but also guarantees the fairness of channel access. Nevertheless, the mobile node may not be able to access the network because it does not meet the constraints of the control packet scheduling, resulting in delayed transmission.

To some extent, the above protocols are capable of achieving their performance goals in the network model that they are concerned with. However, their performance is limited in the scenario where the mobile node wishes to access a one-hop fully connected network composed of static nodes to realize uplink data transmission. Therefore, it is necessary to design a new protocol motivated by the above ones.

III. The Sequence-Scheduled and Query-Based MAC (SQ-MAC) Protocol

A. The Network Scenario and Protocol Overview

Considering the network scenario shown in Fig. 1, where a number of static underwater sensor nodes are randomly placed in a specific three-dimensional space, and a buoy gateway is placed in the center of the water surface of the coverage area. An unmanned underwater vehicle mobile node glides at a constant speed in this space. Underwater static nodes and the mobile nodes are traffic generated nodes, which use half-duplex and omnidirectional acoustic communication. The buoy serves as the common receiver for all traffic generated nodes, and is equipped with underwater acoustic and radio frequency modems. After it collects the data packets transmitted by the underwater node through the upstream underwater acoustic link, it then transfers the received data packets to the shore station through the radio link.

Underwater static nodes and the buoy constitute a one-hop fully connected network, that is, each static node and the buoy are within the maximum communication range of each other, there are no hidden terminals and exposed terminals[26,27]. The

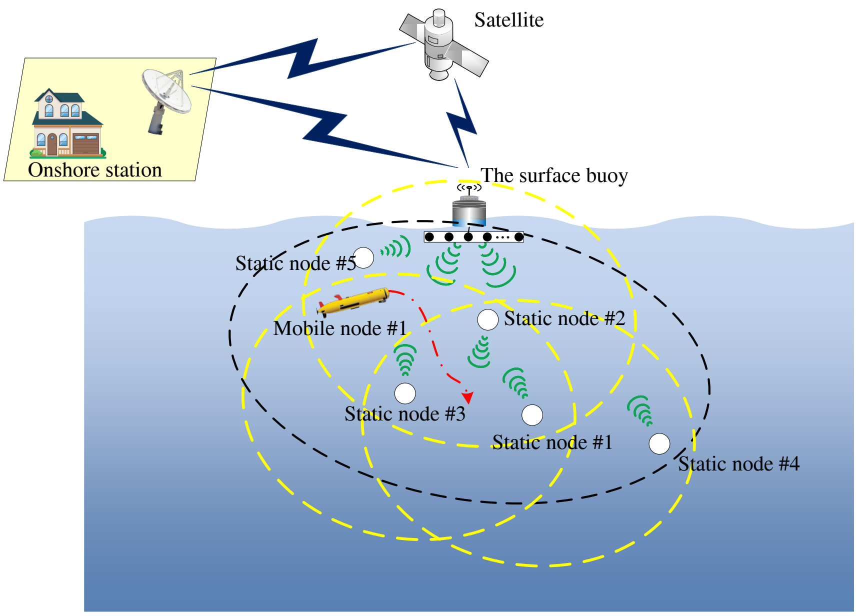

Figure 1 The network scenario with a mobile node

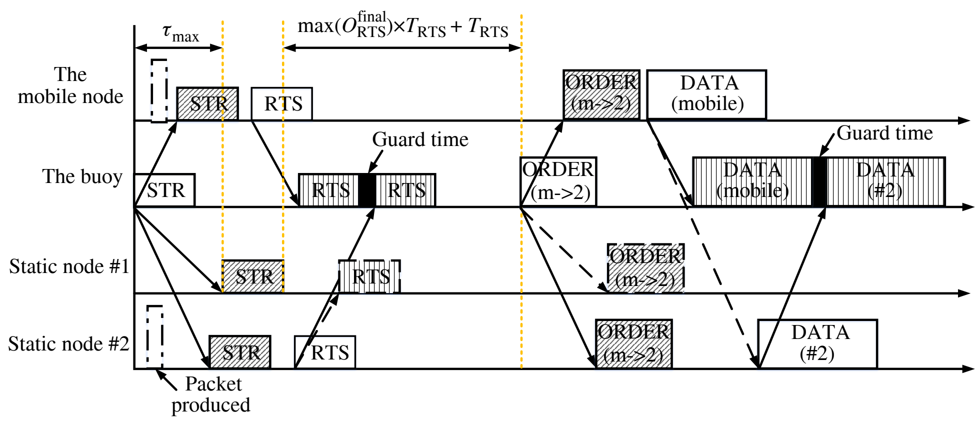

Figure 2 Sequence diagram of the SQ-MAC protocol with mobile node's RTS packet

mobile node is always within the maximum communication range of the buoy, but not always within the communication range of other underwater static nodes.

The SQ-MAC protocol adopts a receiver-initiated 3-way (Start-to-Reserve, STR/Request-to-Send, RTS/ORDER) or 4-way (STR, RTS, QUERY, START) handshake according to whether the RTS control packet of the mobile node is received by the buoy. The premise for the protocol to operate properly is that the surface buoy and underwater static nodes have obtained the adjacency matrix of the network graph during the network initialization, and the mobile node can also learn its distance to the buoy and other underwater static nodes through its own positioning system. The protocol no longer requires precise time synchronization after the network initialization. Figs. 2 and 3 show the sequence diagram of the protocol with and without the mobile node's RTS, respectively. We detail the workflow of the protocol in section III.B.

B. How the Protocol Works

1) Handshake Initiated by the STR Packet: When the surface buoy is in an idle state, it initiates a handshake interaction by broadcasting the STR packet. To collect the reservation information of underwater static nodes as much as possible after a round of the handshake and avoid a long waiting time caused by packet loss or no reservation, the buoy sets a waiting timer when broadcasting the STR packet. If no reservation control packet is received from any underwater nodes after the timer expires, the buoy broadcasts the next STR packet according to current traffic load to initiate another handshake. The duration of the timer will be further explained in section III.B.2).

2) Channel Reservation Using the RTS Packet: When an underwater static node receives the STR packet, it checks its

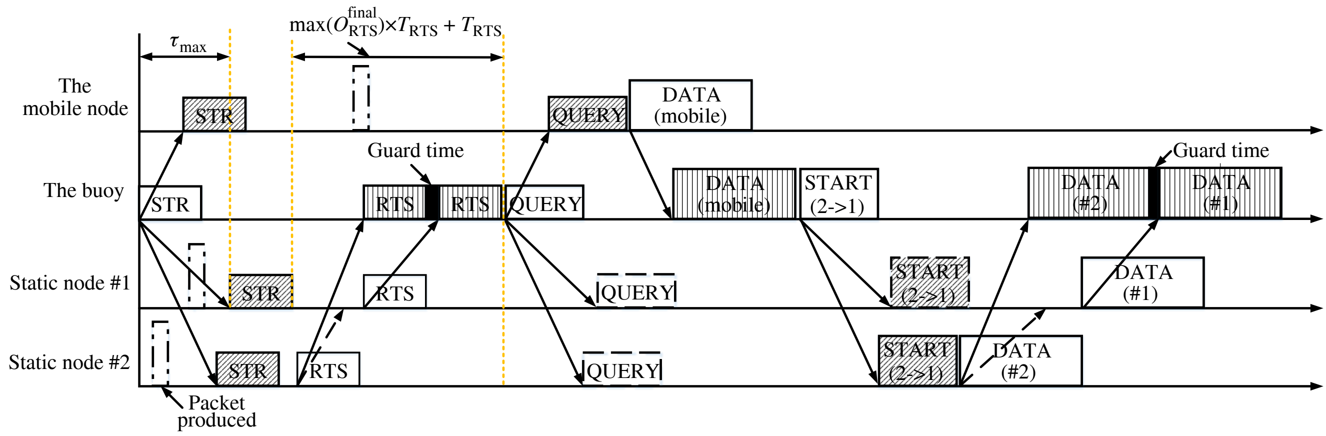

Figure 3 Sequence diagram of the SQ-MAC protocol without mobile node's RTS packet

own buffer and responds with the RTS packet for the channel reservation if there are any data packets that need to be sent. The SQ-MAC protocol allows multiple static nodes to send RTS packets during a handshake. Since the network composed of static nodes is fully connected, according to the theorem that the sum of the two sides of a triangle is greater than the third side, the static node with ID i transmits the RTS packet immediately upon receiving the STR packet will not interfere with the reception of the STR by the static node with ID j, if $\tau_{buoy,i} < \tau_{buoy,j}$. Therefore, when planning the transmission moment of the RTS packet, the collision of multiple RTS packets at the buoy is mainly considered.

Here, we develop a mechanism to adjust the RTS transmission order. A static node with ID i first calculates the original RTS transmission order $O_{RTS,i}^{ori}$ according to (1), where $\lceil x \rceil$ means the minimum integer larger than x.

$$O_{RTS,i}^{ori} = \left\lceil \frac{\tau_{buoy,i}}{T_{RTS}} \right\rceil, \quad i = 1,2,3,\cdots,N. \tag{1}$$

(2) is the time taken by the buoy to receive the RTS control packets sent by the static nodes with ID i and ID j.

$$\begin{cases} \mathrm{Ival}_{recv\_RTS}^{i} = [t_{send\_RTS}^{i} + \tau_{buoy,i}, t_{send\_RTS}^{i} + \tau_{buoy,i} + T_{RTS}], \\ \mathrm{Ival}_{recv\_RTS}^{j} = [t_{send\_RTS}^{j} + \tau_{buoy,j}, t_{send\_RTS}^{j} + \tau_{buoy,j} + T_{RTS}]. \end{cases} \tag{2}$$

Therefore, in the case that $\tau_{buoy,i} < \tau_{buoy,j}$, to ensure the RTS packets sent by these two static nodes will not collide at the buoy, (3) should be satisfied.

$$(t_{send\_RTS}^{j} + \tau_{buoy,j}) - (t_{send\_RTS}^{i} + \tau_{buoy,i} + T_{RTS}) \geqslant T_{pro}. \tag{3}$$

If the static nodes with IDs i and j transmit the RTS packets immediately after receiving the STR, $t_{send\_RTS}^{i}$ and $t_{send\_RTS}^{j}$ can be calculated as (4), where Δ_{handle} is the hardware processing time.

$$\begin{cases} t_{send\_RTS}^{i} = t_{send\_STR}^{buoy} + \tau_{buoy,i} + T_{STR} + \Delta_{handle}, \\ t_{send\_RTS}^{j} = t_{send\_STR}^{buoy} + \tau_{buoy,j} + +T_{STR} + \Delta_{handle}. \end{cases} \tag{4}$$

Table 1 Notations used for elaborating the SQ-MAC protocol

Notation	Description
T_{wait}^{RTS}	The moment at which the buoy finishes waiting the RTS packet
$\tau_{buoy,i}$	Propagation delay between a static node i and the buoy
$\tau_{i,j}$	Propagation delay between a static node i and a static node j
τ_{max}	Maximum propagation delay of the network (except the mobile node)
$O_{RTS,i}^{ori}$	The original RTS transmission order of a static node i
$O_{RTS,i}^{final}$	The final RTS transmission order of a static node i
O_{RTS}^{final}	The final RTS transmission order of all the static nodes
$O_{RTS,mobile}^{ori}$	The original RTS transmission order of the mobile node
$O_{RTS,mobile}^{final}$	The final RTS transmission order of the mobile node
T_{RTS}	Transmission time of each fixed-length RTS packet
T_{DATA}	Transmission time of each fixed-length DATA packet
T_{pro}	Guard time interval, which equals T_{RTS}
$t_{send\_STR}^{buoy}$	The moment when the buoy transmits the STR packet
$t_{recv\_STR}^{i}$	The moment when a static node i finishes receiving the STR packet
$t_{send\_RTS}^{i}$	The moment when a static node i transmits the RTS packet
N	The number of underwater static nodes

Substituting (4) into (3), we get (5).

$$2\tau_{buoy,j} - 2\tau_{buoy,i} \geqslant T_{pro} + T_{RTS}. \tag{5}$$

T_{pro} is the guard interval of arrival time of RTS packets sent from different nodes, which is set in consideration of delay deviation. It has been indicated in Tab. 1 that $T_{pro} = T_{RTS}$, (5) is thus equivalent to (6).

$$\tau_{buoy,j} - \tau_{buoy,i} \geqslant T_{RTS}. \tag{6}$$

According to (6), (7) can be derived.

$$\frac{\tau_{buoy,j}}{T_{RTS}} - \frac{\tau_{buoy,i}}{T_{RTS}} \geqslant 1. \tag{7}$$

Considering (7) and (1), to realize the non-collision arrival of the RTS packets sent by each static node to the buoy, the original RTS transmission orders of all the static nodes are firstly arranged in an ascending order. Then they are adjusted as (8). Finally, the final RTS transmission orders of all static nodes are determined. We assume $O_{\mathrm{RTS},i}^{\mathrm{ori}} \leqslant O_{\mathrm{RTS},j}^{\mathrm{ori}}$, $i < j$ in (8).

$$\begin{cases} O_{\mathrm{RTS},i}^{\mathrm{final}} = O_{\mathrm{RTS},i}^{\mathrm{ori}}, \\ O_{\mathrm{RTS},j}^{\mathrm{final}} = O_{\mathrm{RTS},i}^{\mathrm{ori}} + 2, & \text{if } (O_{\mathrm{RTS},j}^{\mathrm{ori}} - O_{\mathrm{RTS},i}^{\mathrm{ori}} < 2), \\ O_{\mathrm{RTS},j}^{\mathrm{final}} = O_{\mathrm{RTS},j}^{\mathrm{ori}}, & \text{if } (O_{\mathrm{RTS},j}^{\mathrm{ori}} - O_{\mathrm{RTS},i}^{\mathrm{ori}} \geqslant 2). \end{cases} \tag{8}$$

At this time, the timeout of the waiting timer of the buoy is the time when the buoy receives the RTS packet sent by the farthest static node , as shown in (9), where $\max(O_{\mathrm{RTS}}^{\mathrm{final}})$ is the maximum final RTS transmission order of all static nodes,

$$T_{\mathrm{wait}}^{\mathrm{RTS}} = t_{\mathrm{send,STR}}^{\mathrm{buoy}} + \tau_{\max} + T_{\mathrm{STR}} + \max(O_{\mathrm{RTS}}^{\mathrm{final}}) \times T_{\mathrm{RTS}} + T_{\mathrm{RTS}}, \tag{9}$$

and the moment when a static node i with data packets to be sent transmits the RTS packet is determined by (10). That is, a static node must ensure the moment when to send the RTS packet is later than the moment when it receives the STR packet. At the same time, it must guarantee that the RTS it sends does not collide with the RTS packets sent by other static nodes at the buoy.

$$t_{\mathrm{send\_RTS}}^{i} = \max(t_{\mathrm{recv\_STR}}^{i}, t_{\mathrm{recv\_STR}}^{i} - \tau_{\mathrm{buoy},i} + O_{\mathrm{RTS},i}^{\mathrm{final}} \times T_{\mathrm{RTS}}). \tag{10}$$

Similarly, if the mobile node has data packets to send, it calculates the current propagation delay with the buoy by itself when it receives the STR packet and obtains its original RTS transmission order $O_{\mathrm{RTS,mobile}}^{\mathrm{ori}}$ according to (1). Next, it compares $O_{\mathrm{RTS,mobile}}^{\mathrm{ori}}$ with the final RTS transmission orders of all the static nodes and adjusts $O_{\mathrm{RTS,mobile}}^{\mathrm{ori}}$ as (11), where $O_{\mathrm{RTS}}^{\mathrm{final,sorted}}$ is the set obtained by sorting the elements in $O_{\mathrm{RTS}}^{\mathrm{final}}$ in ascending order, $i = 1, 2, 3, \cdots, N$.

$$\begin{cases} O_{\mathrm{RTS,mobile}}^{\mathrm{ori}} = O_{\mathrm{RTS},i}^{\mathrm{final,sorted}} + 2, & \text{if } 0 < |O_{\mathrm{RTS,mobile}}^{\mathrm{ori}} - O_{\mathrm{RTS},i}^{\mathrm{final,sorted}}| < 2, \\ O_{\mathrm{RTS,mobile}}^{\mathrm{ori}} = O_{\mathrm{RTS,mobile}}^{\mathrm{ori}}, & \text{else}. \end{cases} \tag{11}$$

After traversing all the elements in $O_{\mathrm{RTS}}^{\mathrm{final,sorted}}$, let $O_{\mathrm{RTS,mobile}}^{\mathrm{final}} = O_{\mathrm{RTS,mobile}}^{\mathrm{ori}}$. If the mobile node can finally find the RTS transmission order that satisfies (12), the order is substituted into (10) to determine the transmission moment of its own RTS packet; otherwise, the mobile node does not respond in this handshake and waits for the QUERY packet sent by the buoy.

$$O_{\mathrm{RTS,mobile}}^{\mathrm{ori}} \leqslant O_{\mathrm{RTS,mobile}}^{\mathrm{final}} < \max(O_{\mathrm{RTS}}^{\mathrm{final}}). \tag{12}$$

3) The Buoy Retrieves the RTS Packet Sent by the Mobile Node: When the waiting timer expires, the buoy retrieves the RTS sent by the mobile node from the received RTS packets. If the RTS sent by the mobile node is retrieved, the buoy skips to step 5) to perform corresponding operation. Otherwise, there are two possible cases. One is that the mobile node has no data packets to send when it receives the STR packet. The other is that the final RTS transmission order of the mobile node does not satisfy (12). To avoid the reservation failure and the data transmission delay of the mobile node caused by the second case, the buoy broadcasts the QUERY packet after the retrieval to acquire the situation of the mobile node and after receiving the reply from the mobile node, it jumps to step 5).

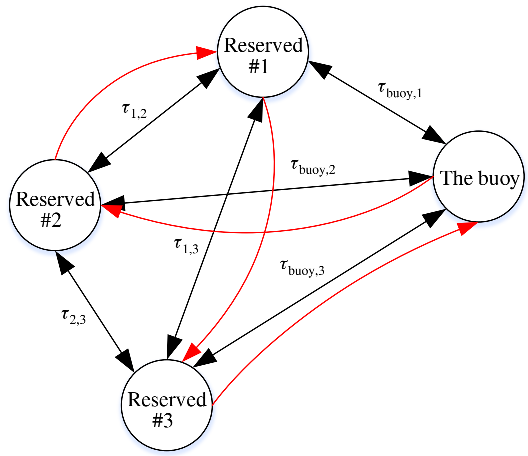

Figure 4 The adjacency graph of the reserved nodes

4) The Mobile Node Responses to the QUERY: After the mobile node receives the QUERY packet, it directly transmits the cached data packets if there are; otherwise, it responds with the NONE packet to inform the buoy that there are currently no data packets need to be transmitted.

5) The Buoy Calculates the Transmission Order of Data Packets: When the mobile node successfully sends the RTS in the STR-RTS interaction stage, it hovers at the corresponding position at that time and waits for the control command of the buoy. Therefore, the distance from the mobile node to the buoy is considered to remain unchanged before the transmission of data packets of the mobile node is completed. To relax the requirements for time synchronization, each reserved node sends data packets in sequence through the carrier sensing, that is, the reserved underwater node in the back order can only send its data packets after hearing the data packets sent by the node in the front order.

Assuming that the transmission order of DATA packets of the reserved nodes in current round is 2,1,3.

As shown in Fig. 4, the node with ID 2 will send its data packets once receiving the ORDER or the START packet sent by the buoy. Then, the node with ID 1 calculates the transmission time of data packets only when it senses the carrier from its previous node, the ID of which is 2. Similarly, the node with ID 3 begins to send data packets after sensing the carrier from the node with ID 1. It can be seen that the idle listening time of the channel $T_{\text{channel}}^{\text{idle}}$ is $\tau_{\text{buoy},2} + \tau_{2,1} + \tau_{1,3} + \tau_{3,\text{buoy}}$. To improve the network throughput, the optimal order of the reserved nodes to transmit data packets is the order that minimizes the idle listening time of the channel. To be specific, the optimal order can be obtained by solving the problem of finding a shortest path that starts from the buoy, traversing all the reserved underwater nodes once and finally return to the buoy. The above issue is a typical traveling salesman problem (TSP)[28], which is solved by the ant colony algorithm in Ref. [13]. Once the transmission order of data packets of the reserved nodes is scheduled, the buoy informs the reserved nodes by broadcasting the ORDER packet or the START packet.

6) Reserved Nodes Send Data Packets in Sequence: The reserved nodes extract the transmission order list of the data packets from the ORDER packet or the START packet. The node with the first order sends its data packets immediately after receiving the ORDER packet or the START packet. Other nodes continue to listen to the channel until they receive the data packets sent by its previous node. For instance, assume the number of data packets sent by the reserved node in the first order is m. Then, the time $t_{\text{send\_DATA}}^{\text{ORDER\_2}}$ at which the reserved node in the second order transmits data packets is determined by (13),

$$\begin{cases} t_{\text{recv\_DATA}}^{\text{ORDER\_1}} = t_{\text{send\_DATA}}^{\text{ORDER\_1}} + \tau_{\text{buoy,ORDER\_1}} + T_{\text{DATA}} \times m + T_{\text{pro}}, \\ t_{\text{send\_DATA}}^{\text{ORDER\_2}} = \max(t_{\text{send\_DATA}}^{\text{ORDER\_1}} + \tau_{\text{ORDER\_1,ORDER\_2}} + \\ \qquad T_{\text{DATA}} \times m, t_{\text{recv\_DATA}}^{\text{ORDER\_1}} - \tau_{\text{buoy,ORDER\_2}}), \end{cases} \tag{13}$$

where $t_{\text{send\_DATA}}^{\text{ORDER\_1}}$ is the moment when the reserved node in the first order sends data packets, $\tau_{\text{ORDER\_1,ORDER\_2}}$ is the propagation delay between the reserved node in the first order and the reserved node in the second order, $t_{\text{recv\_DATA}}^{\text{ORDER\_1}}$ is the moment when the buoy finishes the reception of data packets of the reserved node in the first order. The data packets transmission time of the other reserved nodes in the later order can be deduced as (13).

IV. Simulations and Discussions

In this section, the performance of the SQ-MAC protocol in terms of nodal throughput, average end-to-end delay of static nodes, access delay and successful access probability of the mobile node are evaluated. Two existing MAC protocols, namely, TDMA[29] and NP-CSMA[30] were taken as the reference in our simulation. The TDMA is a schedule-based MAC protocol, which allocates fixed transmission time slots to each node. The NP-CSMA is a contention and carrier sensing based MAC protocol, which performs random back-off when the channel is detected to be busy.

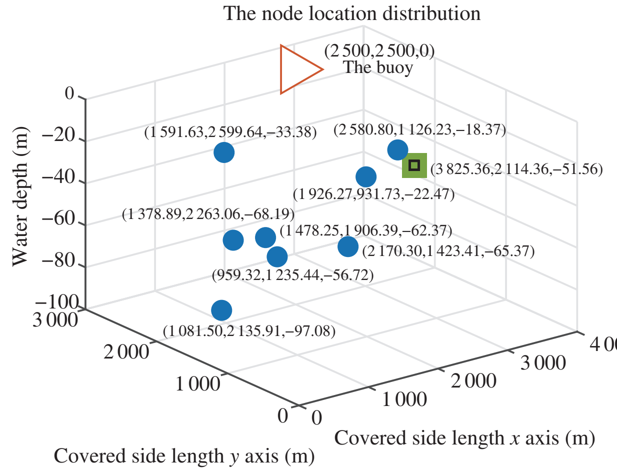

Figure 5 The node location distribution in a random experiment

A. Model and Parameters

Our simulation model consisted of eight static nodes and a mobile node deployed randomly in the cubic area of 5 000 m×5 000 m×100 m. The buoy was located at the center of the water surface; the position coordinates of which were (2 500 m, 2 500 m, 0 m). The maximum communication range of the buoy and static nodes was 2 km. The mobile node moved at a speed of 4 knots. Fig. 5 shows the location distribution of nodes in one random trial. In Fig. 5, the triangular one is the buoy; the circular ones are underwater static nodes and the square one is the mobile node; the black overlapping parts in the square are different positions during the movement of the mobile node.

We assumed the data transmission rate was 1 kbit/s and the acoustic propagation speed was 1 500 m/s. The traffic rate of underwater static nodes and the mobile node followed the Poisson distribution with the parameter λ. Considering the requirement to specify the transmission order of packets, the length of the ORDER and the START packet was 120 bits. Except for that, other control packets (i.e., STR, RTS, NONE) were all 48 bits long. The results of 5 different network topologies with 10 random trials corresponding to each λ were averaged as the final simulation result, and the duration of each random experiment was 1 800 s. Here, the channel was also assumed to be error-free, so that all packet losses were purely based on the performance of the MAC protocols.

The metrics are defined as follows. The nodal throughput characterizes the efficiency of the network, which is the most intuitive performance of the protocol performance. Referring to [10], the definition of the nodal throughput is given as

$$\text{nodal throughput} = \frac{1}{N} \times \frac{P_{\text{total}}^{s} \times L_{\text{packet}}}{T_{\text{sim}} \times R_{\text{bit}}}, \tag{14}$$

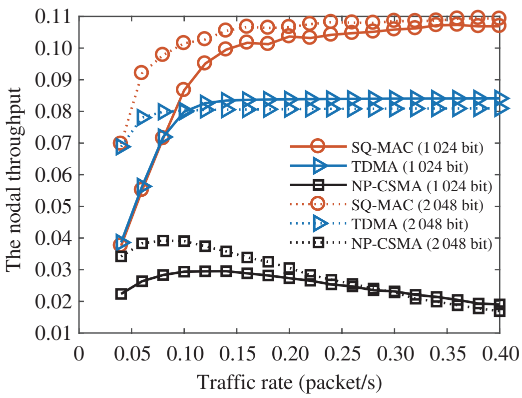

Figure 6 Nodal throughput

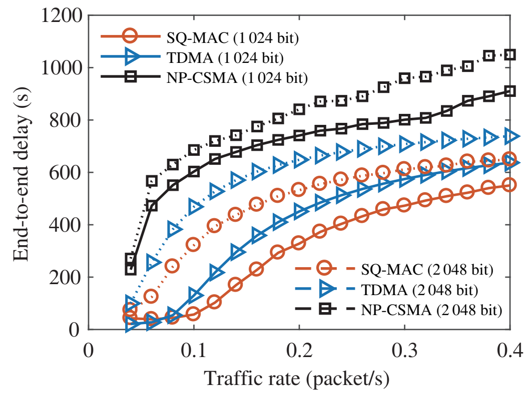

Figure 7 Average end-to-end delay

where $P^{\rm s}_{\rm total}$ is the total number of packets sent by static nodes successfully received by the buoy; N is the number of static nodes; $L_{\rm packet}$ is the length of each packet in bit; $T_{\rm sim}$ is the simulation duration and $R_{\rm bit}$ is the data transmission rate in bit/s.

The average end-to-end delay of static nodes $\text{Delay}_{\rm static}$ and the access delay of the mobile node $\text{Delay}_{\rm mobile}$ can be calculated as (15) and (16), respectively, where $T^k_{\rm recv,s}$ is the moment when the kth packet is generated by static nodes is received; $T^k_{\rm pro,s}$ is the moment when the kth packet is generated by static nodes; $P^{\rm m}_{\rm total}$ is the number of packets sent by the mobile node that are successfully received by the buoy; $T^k_{\rm recv,m}$ is the moment when the kth packet generated by the mobile node is received, and $T^k_{\rm pro,m}$ is the moment when the kth packet is generated by the mobile node.

$$\text{Delay}_{\rm static} = \frac{\sum_{k=1}^{P^{\rm s}_{\rm total}}(T^k_{\rm recv,s} - T^k_{\rm pro,s})}{P^{\rm s}_{\rm total}}, \tag{15}$$

$$\text{Delay}_{\rm mobile} = \frac{\sum_{k=1}^{P^{\rm m}_{\rm total}}(T^k_{\rm recv,m} - T^k_{\rm pro,m})}{P^{\rm m}_{\rm total}}. \tag{16}$$

The successful access probability is shown in (17). $M^{\rm mobile}_{\rm prod}$ is the number of packets generated by the mobile node during the simulation.

$$P_{\rm access} = \frac{P^{\rm m}_{\rm total}}{M^{\rm mobile}_{\rm prod}} \times 100\%. \tag{17}$$

B. Results and Discussions

1) For Static Networks: Figs. 6 and 7 show the performance of the SQ-MAC protocol and the other two reference protocols when there are no mobile nodes in the network.

As shown in Fig. 6, under the same packet length, the nodal throughputs of both the proposed SQ-MAC and TDMA protocols increase first and then stabilize with the increase of the traffic rate, while the throughput of the NP-CSMA protocol decreases with the increase of the traffic rate after reaching the maximum. The main reason is that the probability of collision increases as the traffic rate increases and the time spent in back-off and listening also increases accordingly, so the number of data packets sent by the underwater nodes in the simulation reduces and the channel utilization declines. However, both the SQ-MAC and TDMA protocols avoid the collision at the receiver through sequence-scheduled reservation and fixed allocation, so the channel transmission capacity is saturated and the throughput remains stable with the increase of the traffic rate. When the packet length is 1 024 bit, the maximum throughput of the proposed SQ-MAC protocol is 0.107 3, which outperforms the TDMA and NP-CSMA ones by around 29.28% and 257.67%, respectively. When the packet length is 2 048 bit, the maximum throughput of the proposed SQ-MAC protocol is 0.109 5, which is about 1.35 times and 2.79 times of the TDMA and NP-CSMA ones. These results show that the sequential scheduling of the SQ-MAC is more efficient than the fixed allocation of the TDMA. Moreover, as the length of each data packet increases, the corresponding traffic rate decreases when the saturation throughput is reached, and the throughput of the NP-CSMA decays faster after reaching the maximum throughput.

From Fig. 7, we can see that the average end-to-end delay of the SQ-MAC is lower than the other two protocols. This is because the SQ-MAC plans the optimal data packets transmission order for the reserved nodes after the handshake which reduces the waiting time of the nodes, while the NP-CSMA takes a long time in listening and back-off before data transmission and the TDMA also allocates time slots to the nodes which have no data to send. Except for these, we can find that as the length of each data packet increases, the data packets transmission time increases, and the end-to-end delay also prolongs.

2) For the Network with a Mobile Node: Figs. 8∼11 show the performance of these three protocols when there is a mobile node in the network.

Figs. 8 and 9 show the nodal throughput and average end-to-end delay of the protocols versus the traffic rate, respectively. It can be observed that the throughput of the proposed

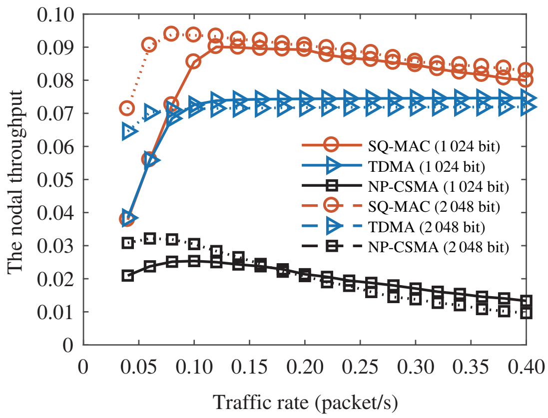

Figure 8 Nodal throughput

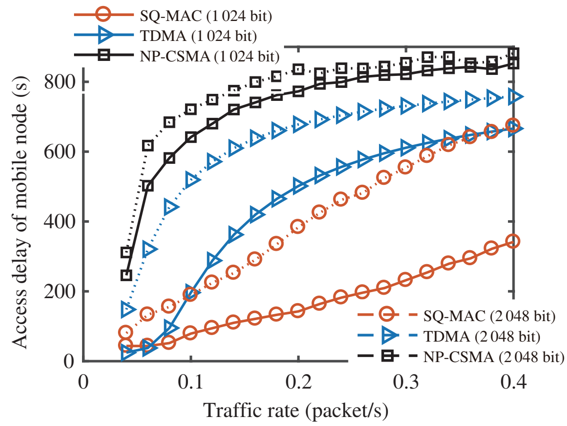

Figure 10 Access delay of the mobile node

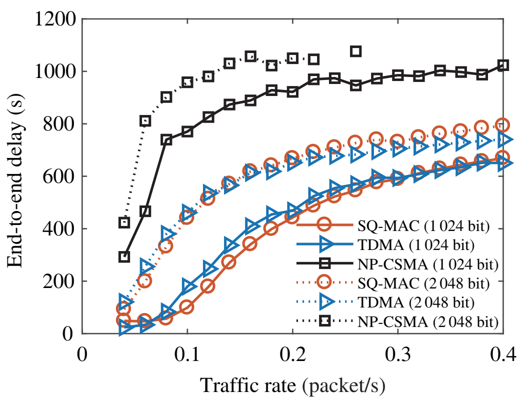

Figure 9 Average end-to-end delay

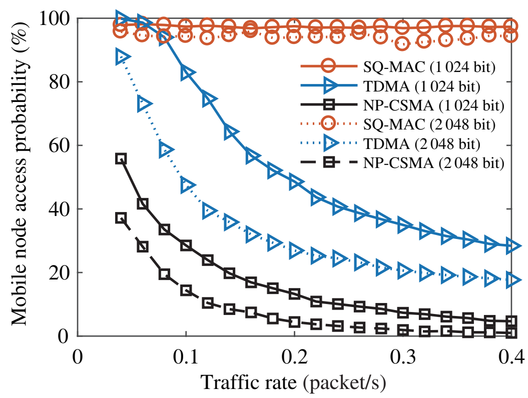

Figure 11 Access probability of the mobile node

SQ-MAC protocol is still better than that of the TDMA and the NP-CSMA in the network with a mobile node, the maximum throughput of the proposed SQ-MAC protocol is 0.088 when the packet length is 1 024 bit, which is about 1.18 times and 3.48 times of the TDMA and the NP-CSMA. When the packet length is 2 048 bit, the maximum throughput of the proposed SQ-MAC protocol is 0.093 8, which is about 1.30 times and 2.76 times of the TDMA and the NP-CSMA. However, in the SQ-MAC, the buoy initiates an inquiry again to interact with the mobile node if the RTS packet sent by the mobile node is not received during the STR-RTS stage, which occupies the data packets transmission time of the reserved static nodes. Therefore, the maximum throughput of the SQ-MAC has a certain degree of decrease compared to that in Fig. 6. Moreover, the heavier the traffic rate is, the longer it takes to interact with the mobile node alone, so the throughput shows a downward trend. Since the TDMA protocol adjusts the time slot size according to the length of each data packet, and only one more time slot is allocated for the mobile node, its maximum throughput does not drop significantly compared to that in Fig. 6. As the traffic rate increases, the nodal throughput still remains stable.

Because the access of the mobile node may occupy the data packets transmission time of the static nodes, the average end-to-end delay of the proposed SQ-MAC increases compared to that in Fig. 7 and is close to that of the TDMA protocol in Fig. 8. When the length of each data packet is 2 048 bit and the traffic rate is greater than 0.2, the average end-to-end delay of the SQ-MAC is slightly higher than that of the TDMA. Due to the access of the mobile node, which exacerbates the collision of the data packet, the NP-CSMA protocol even has an infinite end-to-end delay in a random test when the load is heavier than 0.24.

The access delay of the mobile node is defined as the average duration of a data packet from being produced by the mobile node to being received by the buoy successfully. Fig. 10 shows the access delay of the mobile node of three protocols. It can be seen from Fig. 10 that the access delay of the mobile node of the SQ-MAC is much lower (dropped by 91.37% at most) than that of the other two protocols and the superiority is more obvious when the data packet length is 1 024 bit and the traffic rate is heavy. The main reason is that the buoy in the SQ-MAC protocol actively inquires the mobile node as long as it does not receive the RTS packet sent by the mobile node during the STR-RTS interaction. This ensures the data packets of the mobile node to be transmitted in time.

Fig. 11 shows the access probability of the mobile node. It can be seen that the access probability of the mobile node of both the TDMA and NP-CSMA protocols decreases with the traffic rate increases. Under the same traffic rate, the longer the data packet length is, the lower the access probability is. However, the access probability of the SQ-MAC is always more than 90% under the different data packet lengths and traffic rates, which is higher than that of the other two reference protocols. When the data packet lengths are 1 024 bit and 2 048 bit, the average access probability of the SQ-MAC protocol are 97.4% and 94.11%, respectively. This demonstrates that the query mechanism of the SQ-MAC protocol ensures the access efficiency of the mobile node.

V. CONCLUSION

In this paper, the SQ-MAC protocol is proposed for the scenario where a mobile node accesses a one-hop fully connected network including multiple static nodes to achieve uplink data transmission. Collisions of RTS packets during the handshake phase are avoided through the adjustment mechanism of RTS packets we have proposed. The optimal transmission order of data packets is scheduled by the ant colony algorithm to reduce the idle waiting time of the channel. When the buoy does not receive the RTS packet from the mobile node, the added active query can improve the access probability and reduce the access delay of the mobile node. The simulations show that the proposed SQ-MAC protocol achieves the optimal throughput compared to the TDMA and NP-CSMA protocols, regardless of the existence of the mobile node. When the mobile node exists, the SQ-MAC protocol obtains the highest access probability and the lowest access delay.

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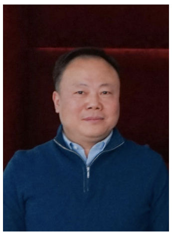

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